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Subj: Final Report Grant No. N00014-95-1-0258

Dear Dr. Curtin,

Enclosed is a hard copy of the FINAL report for work done under the "Coastal Modeling With Optimized Open Boundary Conditions" project (N00014-95-1-0258). The results of the research appear in two published papers, in another paper which is in press, and in three papers which have been submitted to refereed journals.

Please let me know if I can provide any other information.

With best regards.

Sincerely,

Igor Shulman

Enclosure

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FINAL REPORT

COASTAL MODELING WITH OPTIMIZED OPEN BOUNDARY CONDITIONS

GRANT NO: N0OO14-95-1-0258

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OBJECTIVES

Contribute to the development of data assimilation techniques to specify open boundary conditions for coastal models in order to enhance the Navy's capabilities in the development of coastal nowcast/forecast systems. In most applications, coastal models are established as limited area models of fine resolution, for which the open boundary conditions are specified from extraneous sources, usually a deep ocean (basin) model and available observations. This requires the development of techniques to force models with available information along open boundaries and techniques for coupling coastal and basin scale models.

APPROACH

An optimization approach is used to specify open boundary conditions for coastal models. Values of variables on the open boundary are calculated via a specific optimization formulation that provides the best fit to available data (reference values) on the open boundary and to the energy flux through the open boundary.

The optimization formulation is split into barotropic and baroclinic parts. Optimized open boundary conditions (OBCs) are derived in the form of a special linearization of the Bernulli equation for each normal mode. Barotropic OBCs (Shulman and Lewis, 1996, 1995; Shulman 1996) are optimized versions of the radiation type boundary conditions of Flather (1976) and Reid and Bodine (1968). Due to the complexity of normal modal decomposition for varying bathymetry at an open boundary, two alternative approaches were proposed to derive baroclinic boundary condition: a simplified modal baroclinic condition (this simplification represents an average over all the baroclinic modes, and does not require normal mode decomposition; see Shulman and Lewis (1996)), and the use of empirical orthogonal functions (EOFs) instead of normal modes.

The proposed technology for coupling a fine resolution limited area coastal model

(LAM) with a coarse resolution basin scale model is based on optimized open boundary conditions. Two schemes are used to couple the models. In the first scheme, reference values in the optimization problem are interpolated data from the coarse grid model, and the energy flux is estimated from the interior solution of the LAM. In the second scheme, reference values in the optimization problem are estimated from the governing physics of the LAM (for example, by employing a modified Orlanski condition, Camerlengo and O'Brien, 1980), and the energy flux is estimated from the basin model.

The proposed optimization approach to specify OBCs can be considered as a local data assimilation process (local in time and in space), when available information (for example, sea surface elevation) is assimilated into the model to specify the open boundary conditions. In the same fashion as it is done for the open boundary, we propose assimilation of available data along transects inside the model domain (for example, satellite sea level data).

TECHNICAL ACCOMPLISHMENTS

*The optimized barotropic and baroclinic boundary conditions (OBCs) have been developed for explicit and semi-explicit versions of the Princeton Ocean Model.

*Proposed optimized boundary conditions have been tested and sensitivity studies have been conducted for an idealized channel, the Adriatic Sea and the Yellow Sea.

*Technology to couple basin and limited area coastal models with the use of optimized open boundary conditions is being developed.

*The local data assimilation approach to derive OBCs was extended to assimilate data along transects inside of the model domain of a LAM.

RESULTS

The results of tidal and wind-driven simulations and sensitivity studies show that the application of the optimized versions of radiation type open boundary conditions reduce significantly the error of model predictions compared to the use of non-optimized coun-

terparts. Radiation type open boundary conditions transmit the level of errors in the reference values into the interior model domain, while the optimized versions of these conditions correct the energy input from the reference values and thus result in a reduction in errors (Shulman, 1996).

The results of coupling a fine resolution LAM with a coarse grid model show that the above-mentioned two optimized schemes for coupling models perform superiorly in comparison to one when values on the open boundary of the LAM are simply equal to the interpolated ones from the coarse grid model run. In the framework of each coupling scheme for coupling baroclinic modes, we tested the simplified baroclinic open boundary condition, a decomposition of variables into orthogonal normal modes, and the use of EOF's modes instead of normal modes.

In addition, the approach to derive optimized open boundary conditions was extended to assimilate data along transects inside a model domain. The predictive skill of a model of the Yellow Sea was improved significantly by the use of optimized open boundary conditions and the assimilation of a transect of tidal elevation data at the entrance to the Bohai Bay.

IMPACTS FOR SCIENCE & TECHNOLOGY

Optimized open boundary conditions have been developed for versions of the Princeton Ocean Model, a model that is widely used by the Navy and oceanographic community. The development of such an important component of this model as open boundary conditions and coupling fine and coarse resolutions models enhances the Navy's capabilities in the development of coastal nowcast/forecast models and will provide new possibilities for operational environmental forecasting.

APPLICATION

* Coupling regional, limited-area models with larger-scale models (such as the Navy's layer Global Ocean Model).

* Forcing models with available observations along the open boundaries.

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Shulman, I., and J. K. Lewis, Optimization approach to the treatment of open boundary conditions. *J. Phys. Oceanogra.*, 25, 5, 1006- 1011, 1995.

Shulman, I., 1996: Local data assimilation in specification of open boundary conditions. In press., *J. Atmos. Oceanic Technol.*

PUBLICATIONS

a. Papers published (refereed journals)

Shulman, I. and J. K. Lewis, Optimized boundary conditions for coastal modeling. In *Estuarine and Coastal Modeling.* Ed. Malcolm L. Spaulding and Ralph T. Cheng, 268-282, 1996.

Shulman, I., and J. K. Lewis, Optimization approach to the treatment of open boundary conditions. *J. Phys. Oceanogra.*, 25, 5, 1006- 1011, 1995.

b. Papers accepted (refereed journals)

Shulman, I., 1996: Local data assimilation in specification of open boundary conditions. In press., *J. Atmos. Oceanic Technol.*

c. Papers submitted (refereed journals)

Shulman, I., J. K. Lewis, and J. G. Mayer, 1997: Local data assimilation in the estimation of barotropic and baroclinic open boundary conditions. Submitted to *J. Geophys. Res. (Oceans).*

Lewis J. K., I. Shulman, and A. F. Blumberg, 1997: Assimilation of CODAR observations into ocean models. Submitted to *Continental Shelf Research.*

Shulman, I., J. K. Lewis, A.F.Blumberg and B. Nicholas Kim, 1997: Optimized boundary conditions and data assimilation with application to the M2 tide in the Yellow Sea. Submitted to *J. Atmos. Oceanic Technol.*.

d. Technical Reports/papers (non-refereed)

6. Shulman, I. and J. K. Lewis, 1995: Modeling open boundary conditions by using the optimization approach. Report to the Office of Naval Res., Center for Ocean & Atmosph. Modeling, The Univ. of South. Miss., TR-1/95, 13p.

PRESENTATIONS

Shulman, I., J. K. Lewis, and J. G. Mayer, Optimized open boundary conditions and coupling fine and coarse resolution models, American Geophysical Union, Fall Meeting, 1996.

James K. Lewis, I. Shulman, and A. F. Blumberg, Assimilation of CODAR observations into ocean models, American Geophysical Union, Fall Meeting, 1996.

Shulman, I. and J. K. Lewis, Local data assimilation methods for 3D open boundary conditions, 1996 Ocean Sciences Meeting.

Shulman, I., and J. K. Lewis, Optimized boundary conditions for coastal modeling . The 4th ASCE International Estuarine and Coastal Modeling Conference, 1995.

Shulman, I., Local data assimilation in specification of open boundary conditions. The XXI General Assembly of the International Association for the Physical Sciences of the Oceans (IAPSO), 1995.

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An optimization appraoch is used to specify open boundary conditions for coastal models. Values of variables on the open boundary are calculated via a specific optimization formulation that provides the best fit to available data (reference values) on the open boundary and to the energy flux through the open boundary. The optimized barotropic and baroclinic boundary conditions (OBCs) have been developed for explicit and semi-explicit versions of the Princeton Ocean Model. Proposed optimized boundary conditions have been tested and sensitivity studies have been conducted for an idealized channel, the Adriatic Sea and the Yellow Sea.

Technology to couple basin and limited area coastal models with the use of optimized open boundary conditions is being developed. The local data assimilation approach to derive OBCs was exteded to assimilate data along transects inside of the model domain of a limited area coastal model.

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